

THE YOUNG PLANET-MASS OBJECT 2M1207b:
A COOL, CLOUDY, AND METHANE-POOR ATMOSPHERETRAVIS S. BARMAN¹, BRUCE MACINTOSH², QUINN M. KONOPACKY², CHRISTIAN MAROIS³*Draft version January 27, 2013*

ABSTRACT

The properties of 2M1207b, a young (~ 8 Myr) planet-mass companion, have lacked a satisfactory explanation for some time. The combination of low luminosity, red near-IR colors, and L-type near-IR spectrum (previously consistent with $T_{\text{eff}} \sim 1600$ K) implies an abnormally small radius. Early explanations for the apparent underluminosity of 2M1207b invoked an edge-on disk or the remnant of a recent protoplanetary collision. The discovery of a second planet-mass object (HR8799b) with similar luminosity and colors as 2M1207b indicates that a third explanation, one of a purely atmospheric nature, is more likely. By including clouds, non-equilibrium chemistry, and low-gravity, an atmosphere with effective temperature consistent with evolution cooling-track predictions is revealed. Consequently 2M1207b, and others like it, requires no new physics to explain nor do they belong to a new class of objects. Instead they most likely represent the natural extension of cloudy substellar atmospheres down to low T_{eff} and $\log(g)$. If this *atmosphere only* explanation for 2M1207b is correct, then very young planet-mass objects with near-IR spectra similar to field T dwarfs may be rare.

Subject headings: planetary systems — stars: atmospheres — stars: low-mass, brown dwarfs, stars: individual (2MASSW J1207334–393254)

1. INTRODUCTION

2M1207b is a planet-mass companion orbiting the young brown dwarf 2M1207A at a projected separation of ~ 46 AU (Chauvin et al. 2004, 2005). As a member of the ~ 8 Myr old TW Hydra association (Gizis 2002), 2M1207b is one of the youngest companions of its mass ($\sim 2 - 5 M_{\text{Jup}}$) ever imaged. Regardless of how the system formed, 2M1207b provides a unique look into the atmospheric properties of giant planets and brown dwarfs in the very early stages of their evolution.

Soon after 2M1207b was discovered, it was recognized that its low luminosity and red near-IR colors were seemingly inconsistent. With $m_K = 16.93 \pm 0.11$ (Chauvin et al. 2004), a K -band bolometric correction of 3.25 ± 0.14 (Mamajek 2005), and a distance of 52.4 ± 1.1 pc (Ducourant et al. 2008), 2M1207b has a luminosity of $\log L/L_{\odot} = -4.73 \pm 0.12$. With this luminosity and an age of 8^{+4}_{-3} Myr (Chauvin et al. 2004), brown dwarf cooling tracks (Baraffe et al. 2003) predict⁴ $T_{\text{eff}} = 936 - 1090$ K, $\log(g) = 3.5 - 3.8$ (cgs units), radius = $1.34 - 1.43 R_{\text{Jup}}$, and a mass of $2.3 - 4.8 M_{\text{Jup}}$. The red near-IR colors (e.g., $H - K = 1.16 \pm 0.24$; Chauvin et al. 2004) and near-IR spectra of 2M1207b, on the other hand, are indicative of a mid to late L spectral type and effective temperature of ~ 1600 K (Mohanty et al. 2007; Patience et al. 2010). Such a combination of high effective temperature and low luminosity would require a radius of $\sim 0.7 R_{\text{Jup}}$, about a factor of two below evolution model predictions. Under the assumption that

the higher T_{eff} is correct, two possible explanations for the apparent underluminosity of 2M1207b have been put forward. An edge-on disk, albeit with unusual characteristics, could provide the necessary 2.5 mags of gray extinction to accommodate a larger and more reasonable radius (Mohanty et al. 2007). A more provocative suggestion requires 2M1207b to be the hot afterglow of a recent protoplanetary collision allowing it to be simultaneously hot and small (Mamajek & Meyer 2007).

Both of these early explanations for the observed properties of 2M1207b hinge upon the effective temperature being as high as 1600 K. Earlier estimates of T_{eff} were likely lead astray by the lack of color- T_{eff} relationships properly calibrated for young, planet-mass objects and the lack of model atmospheres spanning a broad enough range of cloud and chemical parameters to encompass objects like 2M1207b. The discovery of HR8799b (Marois et al. 2008), a second planet-mass object with similar near-IR colors and luminosity as 2M1207b, motivates this new model atmosphere study of 2M1207b, as it is highly unlikely that either the edge-on disk or recent-collision explanation applies to both objects.

In this Letter, an atmosphere-only explanation for the observed properties of 2M1207b is presented. A combination of clouds of modest thickness and non-equilibrium CO/CH₄ ratio is shown to simultaneously reproduce both the observed photometric and spectroscopic properties of 2M1207b, with bulk properties consistent with evolution model predictions. Such an explanation was touched upon in several recent papers (Currie et al. 2011; Skemer et al. 2011; Barman et al. 2011), but here the atmosphere of 2M1207b is explored in more detail.

2. CLOUDS

The properties of brown dwarfs and giant planets are known to be influenced by atmospheric cloud opacity and it is well established that clouds play a central role in

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⁴ The ranges in predicted values come from the luminosity and age uncertainties.

the transition from spectral types L to T (Allard et al. 2001). Early work on brown dwarf atmospheres approached cloud modeling phenomenologically, parameterizing the problem with an emphasis on vertical mixing (Ackerman & Marley 2001). Cloudy and cloud-free limits provide useful insight into the expected spectroscopic and photometric trends but often fail, unsurprisingly, to match individual brown dwarfs, especially in the L-to-T transition region (Burrows et al. 2006).

Figure 1 compares field brown dwarfs to 2M1207b and the HR8799 planets in a color-magnitude diagram (CMD). 2M1207b is located between the cloudy and cloud-free limits and, consequently, one should not expect either of these limiting cases to be appropriate when modeling its photometric and spectroscopic properties. Figure 1 shows the path brown dwarfs or giant planets of various effective temperatures would follow in a near-IR CMD if the vertical thickness of clouds is allowed to continuously increase from zero (cloud-free) to well above the photosphere (pure equilibrium clouds). The radius for these tracks, $1.4 R_{\text{Jup}}$, was specifically chosen to match the radius predicted for 2M1207b as discussed above; however, the paths traced by these tracks are otherwise independent of evolutionary models. 2M1207b is intersected by the $T_{\text{eff}} = 1000$ K cloud-track, which is the expected value from evolution models, demonstrating that low-temperature cloudy atmospheres can achieve very red near-IR colors, even with clouds significantly thinner than the extreme limits.

3. NON-LOCAL EQUILIBRIUM CHEMISTRY

If the methane-rich atmospheres of mid to late T dwarfs were in a pure chemical equilibrium state, CO mole fractions would be too small to have a major impact on their spectra. However, CO has been detected in many T dwarfs, suggesting that their atmospheres are out of equilibrium (Noll et al. 1997; Saumon et al. 2000, 2006; Geballe et al. 2009). The most likely mechanism for CO enhancement is vertical mixing from deep layers, where the temperatures and pressures are higher and CO is in ready supply. At photospheric depths and above, the chemical timescale (τ_{chem}) to reestablish an equilibrium CO/CH₄ ratio becomes far greater than the mixing timescale (τ_{mix}), thereby allowing larger CO mole fractions to exist at otherwise methane-dominated pressures. Through the same mixing process, N₂/NH₃ can also depart from local chemical equilibrium (LCE; Saumon et al. 2006; Hubeny & Burrows 2007). The standard non-LCE model quenches the CO and CH₄ mole fractions at the atmospheric pressure (P_q) where $\tau_{\text{mix}} = \tau_{\text{chem}}$, with τ_{mix} computed following Smith (1998). Below the quenching depth ($P > P_q$) the mole fractions for CO and CH₄ are in chemical equilibrium while above ($P \leq P_q$) they are set to the values at P_q .

The mole fractions for CO and CH₄, N(CO) and N(CH₄), at and above P_q are very sensitive to the underlying temperature-pressure (T-P) profile and, thus, are sensitive to gravity, cloud opacity, and metallicity (Hubeny & Burrows 2007; Fortney et al. 2008; Barman et al. 2011). Certain combinations of low gravity and clouds can result in P_q below the CO/CH₄ equilibrium chemistry crossing point (P_{eq}). When P_q is sufficiently deep and $P_q > P_{eq}$, N(CO) can be quenched at its maximum value while N(CH₄) is quenched near

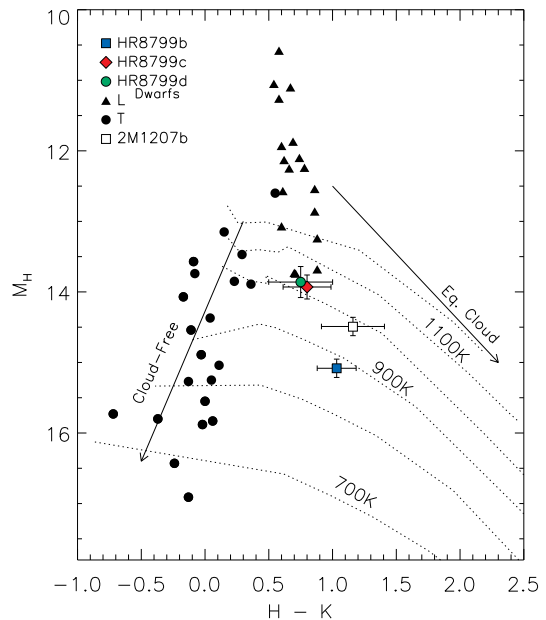


FIG. 1.— Absolute H -band magnitude vs. $H-K$ near-IR color-magnitude diagram for field brown dwarfs (Leggett et al. 2002; Knapp et al. 2004). The planets 2M1207b and HR8799bcd are indicated by symbols with $1-\sigma$ error bars (see legend). Dotted lines show color-magnitude tracks for chemical equilibrium models with radius = $1.4 R_{\text{Jup}}$, $\log(g) = 3.5$, mean particle size equal to $5 \mu\text{m}$ and T_{eff} equal to $700 - 1200$ K in steps of 100 K, from bottom to top. Cloud thickness increases from left to right. The arrows indicate the approximate locations of cloud free (left) and extremely cloudy (right) models, with arrow-direction pointing toward decreasing T_{eff} . The “transition” region, between cloudy and cloud-free atmospheres covers a broad range in the color-magnitude diagram, beyond what is currently occupied by field brown dwarfs.

its minimum. When this situation occurs, the non-LCE CO/CH₄ ratio becomes fairly insensitive to the mixing timescale in the radiative zone (determined by the adopted coefficient of eddy diffusion, K_{zz}). This situation is similar to the N₂/NH₃ chemistry where the NH₃ mole fractions can also be nearly independent of K_{zz} , even in high-gravity cloud-free atmospheres (Saumon et al. 2006; Hubeny & Burrows 2007).

This atmospheric behavior is highly significant to 2M1207b as it allows for a photosphere with much higher N(CO) and much lower N(CH₄) mole fractions at the low T_{eff} predicted by evolution models. Previous studies, focused primarily on field brown dwarfs, present far less severe situations with non-LCE only altering spectra at $\lambda > 4 \mu\text{m}$ where the strongest absorption bands of CO and NH₃ occur (Hubeny & Burrows 2007). At lower surface gravities, however, strong non-LCE effects have been shown to extend well into the near-IR (Fortney et al. 2008; Barman et al. 2011).

4. MODEL COMPARISONS

2M1207b has been observed extensively from the ground and space, with photometric coverage between 0.9 and $\sim 9 \mu\text{m}$ (Chauvin et al. 2004; Song et al. 2006; Mohanty et al. 2007; Skemer et al. 2011). High signal-to-noise J , H , and K spectra are also available (Patience et al. 2010). With the goal of finding a model atmosphere that agrees with these observations and that

has T_{eff} and $\log(g)$ in the range predicted by evolution models, a sequence of atmosphere models was computed covering $T_{\text{eff}} = 900 - 1200$ K and $\log(g)$ from 3.0 to 4.5 (cgs units). The same intermediate cloud (ICM) and non-LCE prescriptions from Barman et al. (2011) were used. Synthetic photometry was generated by convolving synthetic spectra with filter response curves. J , H , and K spectra were produced by convolving the model spectra with a Gaussian filter matching the observed spectral resolution, then interpolated onto the same wavelength points. The best-fit was determined by least-squares minimization.

Figure 2 illustrates the basic structure of the model that best fits the data ($T_{\text{eff}} = 1000$ K and $\log(g) = 4.0$). The atmospheric cloud, composed mostly of Fe and Mg-Si grains, has a base at ~ 3 bar and extends upward before dropping off in number-density at ~ 1 bar. Despite the rapid drop in number-density, the cloud extends across the photospheric depths. Also, P_q (~ 3 bar) is well below the $N(\text{CO})_{\text{eq}} = N(\text{CH}_4)_{\text{eq}}$ point ($P \sim 0.3$ bar), with the CO mole fractions set to the maximum value and CH_4 is close to its minimum value.

While the model cloud and non-LCE properties are determined by free-parameters, they are likely supported by low gravity and efficient vertical mixing. In the convection zone $\tau_{\text{mix}} \propto H_P/V_c$, where V_c is the convective velocity and H_P is the local pressure scale-height. With $K_{\text{zz}} \propto H_P^2/\tau_{\text{mix}} \propto V_c H_P$, K_{zz} increases with decreasing gravity in the convection zone as velocity and scale-height increase. The radiative-convective boundary also shifts toward the photosphere as surface gravity decreases, further suggesting that vertical mixing in the radiative zone near this boundary will also be enhanced in low gravity atmospheres. In the radiative zone it is unclear whether the vertical mixing is predominantly driven by convective overshoot or gravity waves, but the picture emerging from multi-dimensional hydrodynamical simulations in M dwarfs and brown dwarfs indicates that K_{zz} is both depth dependent and easily achieves values $> 10^8 \text{ cm}^2 \text{ s}^{-1}$ (Ludwig et al. 2006; Freytag et al. 2010).

Figure 3 compares the best-fitting model photometry and spectrum to the observations. The model photometry agrees very well with the observations in nearly ever bandpass, with most bands agreeing at 1σ . The model J -band spectrum has about the right slope and nicely reproduces the water absorption starting at $1.33 \mu\text{m}$. At H band, the model also has roughly the correct shape but is slightly too linear across the central wavelengths. The CO band in the K band is very well reproduced by the model but the central wavelength region is again too flat. Skemer et al. (2011) also compare models (Burrows et al. 2006; Madhusudhan et al. 2011) with similar T_{eff} and $\log(g)$ to the same observations; however, these models likely underestimate the non-LCE, as they do not adequately reproduce the near-IR spectrum, especially the CO band at $2.3 \mu\text{m}$. An LCE version of the best-fit non-LCE model is shown in Figure 3 and demonstrates the impact non-LCE has on the near-IR spectrum.

Also shown in Figure 3 is the 1600 K “Dusty” (Allard et al. 2001) equilibrium cloud model often selected as the best match to the near-IR spectra (Mohanty et al. 2007; Patience et al. 2010). The 1600

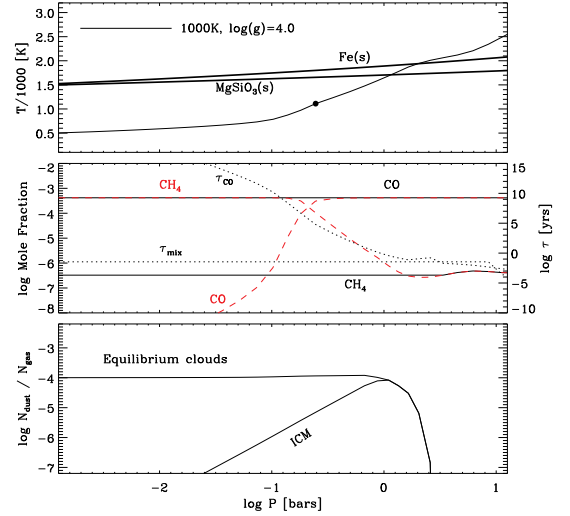


FIG. 2.— Atmospheric properties for the best fitting model for 2M1207b. *Top*: temperature-pressure structure compared to condensation curves for two abundant cloud species. *Middle*: CO and CH_4 mole fractions for equilibrium (dashed, red) and non-equilibrium (solid, with $K_{\text{zz}} = 10^8 \text{ cm}^2 \text{ s}^{-1}$) chemistry. Chemical and mixing timescales are also plotted (dotted lines). *Bottom*: dust-to-gas ratio for the intermediate cloud model (ICM) and the pure equilibrium cloud model.

K model photometry does not agree well with the observations across the full wavelength range. The 1600 K model spectrum, however, is very similar to the best-fit 1000 K model across the K band, but only when the near-IR bands are scaled to match individually (to account for the photometric disagreement for the 1600 K model). In both J and H bands, the 1600 K model overpredicts the peak flux and is noticeably more triangular at H than the observations. At K band, the 1600 K model provides only slightly better agreement with the observations than the 1000 K model.

The remaining differences between the 1000 K model and near-IR spectra can be attributed to an incorrect proportion of dust opacity relative to molecular opacity. Given the simplicity of the cloud model used here such discrepancies are not surprising. Without a doubt, a more parameter-rich cloud model could be used to fine tune the comparison, but it is unlikely that such an exercise will lead to significantly greater insights into the physical properties of the cloud. The primary lesson from this comparison is that atmospheric clouds and chemistry can dramatically alter the spectral shape and potentially lead to errors in effective temperature as great as 50%.

The model comparisons to the photometry provide a new estimate for the bolometric luminosity. The mean luminosity, found by comparing to pure equilibrium models, ICM/non-LCE models and black bodies, is $\log L/L_\odot = -4.68$ with rms of 0.05. This luminosity is consistent with the earlier value mentioned above (based on K -band bolometric corrections).

5. DISCUSSION AND CONCLUSIONS

The best fitting T_{eff} , $\log(g)$, and radius (1000 K, 10^4 cm s^{-2} , and $1.5 R_{\text{Jup}}$) for 2M1207b are consistent with the cooling track predictions discussed above. This model

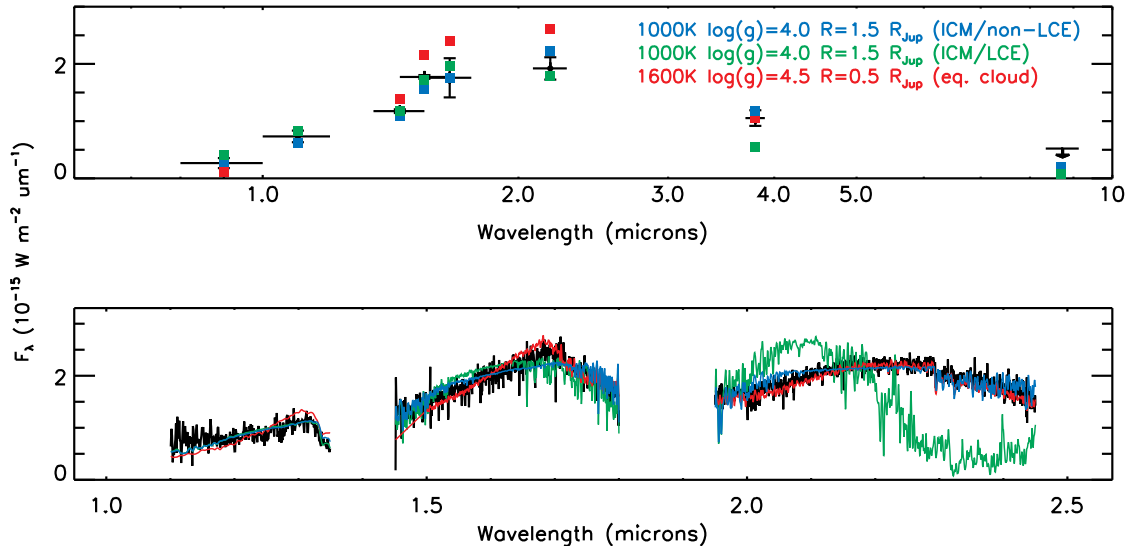


FIG. 3.— Photometric (top) and spectroscopic (bottom) comparison between 2M1207b observations (shown in black, see the text for details) and best-fitting model (blue). For comparison, synthetic photometry and spectra from a 1600 K model (red) with an equilibrium cloud model (aka “Dusty”) along with an LCE model (green) with the same parameters as the non-LCE model. Surface gravities, radii, and effective temperatures are indicated in the legend. All fluxes have been scaled to 10 pc.

demonstrates that including typical cloud thickness and non-LCE are all that is required to reproduce the current observations of 2M1207b. Such a model reminds us that the spectra of brown dwarfs are not strictly a function of temperature and, at young ages, can deviate significantly from expectations derived from older field brown dwarfs. The primary evidence supporting the edge-on-disk and protoplanetary collision hypotheses, was the previously deduced 1600 K effective temperature. A model with this temperature is shown to inadequately reproduce the available photometry and compares no better to near-IR spectra than a cooler cloudy model. Also, the disk-model comparison by Skemer et al. (2011) further weakens the case for an edge-on disk. Consequently, no strong evidence remains for the previous disk or collision hypotheses. This conclusion is independent of the existence of HR8799b, but is certainly supported by it.

The primary atmospheric contributors to the L-type appearance of 2M1207b, despite its low T_{eff} , are clouds extending across the photosphere, thereby reddening the near-IR colors, and non-equilibrium chemistry, establishing a CO/CH₄ ratio that is nearly the reciprocal of what is present in the photospheres of older field T dwarfs. The cloud properties, in particular the thickness, are probably not substantially different from those found in late L dwarfs and the required K_{zz} ($\sim 10^8 \text{ cm}^2 \text{ s}^{-1}$) is well within the range of field dwarfs. Skemer et al. (2011) stress clouds as the primary explanation for the photometric and spectroscopic properties of 2M1207b. However, non-LCE plays an equally important role. Probably the most important underlying distinction between 2M1207b and field brown dwarfs is low surface gravity, provided by its youth and low mass. Without low surface gravity, it is unlikely that clouds or non-LCE would be sufficient to give 2M1207b its current appearance. Such objects, therefore, should not be considered members of a new class, but rather represent the natural extension

of substellar atmospheres to low gravity.

Given their similar masses ($\sim 5M_{\text{Jup}}$), it is possible that 2M1207b and HR8799b represent two distinct states in the evolution of substellar atmospheric properties (despite potentially different formation scenarios). After ~ 20 Myr of cooling, perhaps 2M1207b will spectroscopically evolve into something resembling HR8799b and, eventually, into a traditional looking methane-rich T-dwarf. The very distinct spectra of the two objects (see Figure 15, Barman et al. 2011) would suggest rapid spectral evolution in the first 50 Myr, post formation. It is worth noting that the best-fit models for 2M1207b and HR8799b, though similar in atmospheric parameters, differ in one significant respect – the radius derived from the effective temperature and luminosity. Our model here gives a radius of $1.5 R_{\text{Jup}}$ for 2M1207b, while even the coldest fit to HR8799b in Barman et al. (2011) gives a radius of only $1 R_{\text{Jup}}$. There are several possible explanations for this. First, the recovered radius is of course very sensitive to the effective temperature – a 100 K increase in 2M1207b and a 100 K decrease in HR8799b would remove the discrepancy, though neither would be a good fit to the spectra. Second, this may represent a fundamental difference in their internal state due to different formation scenarios. 2M1207b almost certainly did not form through a core-accretion process as it is highly unlikely that a disk surrounding a low-mass brown dwarf would have had enough material to accrete a giant planet, especially at large separations and in a short time. It is more likely that 2M1207b represents the tail end of binary star formation and, thus, might be expected to follow a similar cooling evolution as brown dwarfs. The formation of the HR8799 planets is less clear but could potentially have involved an accretion period. The “cold start” accretion models of Marley et al. (2007) predict significantly smaller radii for a given age and mass. Although the temperature and luminosity of HR8799b are

too high for the extreme cold start models, the smaller radius may be pointing toward a formation process that involved at least some loss of entropy.

Finally, one can speculate on the implications that 2M1207b and HR8799b might have on the spectral properties for the broader young brown dwarf and planet population. If one adopts, ~ 1500 K as the upper T_{eff} limit for T-dwarfs, then all T dwarfs younger than ~ 100 Myr should be in the planet mass regime ($\lesssim 13 M_{\text{Jup}}$) and should have very low gravity ($\log(g) \lesssim 4.5$). However, if 2M1207b and HR8799b are representative of cool, low gravity, substellar atmospheres, then non-LCE (and possibly clouds) will diminish the strength of CH_4 absorption across the H and K bands, making very young methane dwarfs rare. This prediction, however, is at odds with the tentative discoveries of ~ 1 Myr-old T dwarfs (Zapatero Osorio et al. 2002; Burgess et al. 2009; Marsh et al. 2010). While at least one of these discover-

ies has been drawn into question (Burgasser et al. 2004), if others with strong near-IR CH_4 absorption are confirmed, then it must be explained why substellar objects of similar age and gravity have atmospheres with wildly different cloud and non-LCE properties.

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